The Loss of Energy of an α-Ray Beam in its Passage through Matter. Part I.—*Passage through Air and CO_2.*

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(Communicated by Prof. Sir E. Rutherford, F.R.S.—Received June 21, 1922.)

Introduction.

An α-particle, emitted from a radio-active body, will, during its passage through matter, gradually lose kinetic energy. The experiments of Rutherford and Robinson* have shown that this kinetic energy is converted into an equivalent amount of heat generated in the matter.

These experiments confirm the law of the conservation of energy, but give no indication of the mechanism whereby the energy is given to the surrounding space. This mechanism has been examined theoretically by Thomson,† Bohr,‡ and Darwin,§ who proved that the energy of the α-ray, when passing near an atom, was first given to the electrons, which, in turn, yielded their energy to the atom. The manner in which the α-particle yields its energy to the electrons depends, on the average, on the speed of the α-particle, and on the number and arrangement of the electrons within the atom.

The dependence of the loss of energy of the α-particle on its speed and the structure of the atom has been examined by two methods. The first is that in which the α-particle is projected through different thicknesses of material, its emergent velocity being determined by the deflection produced in a magnetic field. This method has been employed by Rutherford,|| Geiger,¶ and Marsden and Taylor.** This is, *a priori*, the most exact method of attack, but in the experiments there is a weak point, in that the deflected beam must be observed, photographically, or by means of scintillations, and towards the end of the range, when the energy is small, these methods of detection lose their sensitiveness.

It is a surprising fact that, so far, no α-particle has been detected by these methods with a velocity less than 0·4 of the α-particle from radium C. Consequently, it is not known how the last 16 per cent. of the energy of

* E. Rutherford and H. Robinson, 'Phil. Mag.,' vol. 25, p. 312 (1913).
† J. J. Thomson, 'Conduction of Electricity through Gases,' pp. 370–382.
‡ N. Bohr, 'Phil. Mag.,' vol. 25, p. 10 (1913).
§ C. G. Darwin, 'Phil. Mag.,' vol. 23, p. 907 (1912).
|| E. Rutherford, 'Phil. Mag.,' vol. 12, p. 138 (1906).
¶ H. Geiger, 'Roy. Soc. Proc.,' A, vol. 83, p. 505 (1910).
** E. Marsden and T. S. Taylor, 'Roy. Soc. Proc.,' A, vol. 88, p. 443 (1913).

the α-particle is expended, in spite of the fact that this energy is quite considerable.

The second method consists in the study of the amount of the ionisation produced by the α-particle in different parts of its range. If we assume that all the energy of the α-particle is lost in the production of ions, and that the production of each ion requires the same amount of energy, then we can, from the ionisation curve, obtain information about the loss of energy of the α-particle in its passage through a gas. The weak points of this method are (1) that the assumption has no definite theoretical or experimental foundation, and (2) that the method cannot be applied to matter in the solid state.

In the present experiments, which were carried out at the suggestion of Sir Ernest Rutherford, an attempt is made to determine the energy of the α-particle by measuring the heating effect which it can produce after having travelled a definite portion of its range. Any method which is to be used for this purpose must possess the following qualities:—First, since it is necessary to use a narrow beam of α-particles, the energy of a small fraction (about 1000th) of the total number of α-particles emitted from the source has to be measured. If the measuring instrument has a sensitiveness of 10^{-9} calories per second, it would be possible to detect an energy of 0·3 per cent. of the initial energy by determining the range to an accuracy of 1 per cent. Second, if a source of RaC is used, which decays rapidly, the measuring instrument must, in order to obtain a considerable number of readings, have a small thermal capacity, and must also be able to reach a state of equilibrium rapidly. A Boys' radio-micrometer could be used for this purpose, provided it were made sufficiently sensitive and the construction modified to suit the above requirements.

General Theory of the Apparatus.

The directions of modification of the apparatus may be seen from the following considerations. The principal part of the radio-micrometer (fig. 1) consists of a loop of wire of high conductivity, L, terminated at one end by a thermocouple, JT, and supported by means of a quartz fibre, F, in a magnetic field, H. If one end, J, of the thermo-junction is heated, a current circulates in the loop, and a deflection is produced. Having determined the resistance, r, of the thermocouple and the loop (that of the latter being small), the area, S, of the loop, and the torsion-couple per unit twist, μ, of the fibre, an increase, ΔT, in the temperature of one end of the thermocouple produces a deflection, θ, given by

$$\theta = B\,\Delta T\,\frac{SH}{r\mu}, \qquad \text{(i)}$$

where B is a constant depending on the nature of the thermocouple. At first sight, it appears that great sensitiveness could be produced by having S and H large, and μ small. But it is necessary to bear in mind the second condition, which demands that the time for the deflection to reach its maximum value should be small. Taking into account the time, if I is the moment of inertia of the suspended system, we have the following equation of motion—

$$\mathrm{I}\frac{d^2\theta}{dt^2}+\mathrm{K}\frac{d\theta}{dt}+\mu\theta=f(t), \tag{ii}$$

in which K is the damping factor. This damping is a consequence of the eddy currents induced in the loop during its motion in the magnetic field. It is easy to show that K is given by

$$\mathrm{K}=\frac{\mathrm{H}^2\mathrm{S}^2}{r}. \tag{iii}$$

If the roots of the characteristic equation of (ii) are imaginary, damped oscillations will be executed by the system. If the roots are real the maximum displacement is reached in a continuous manner. For the so-called critical point, when the roots are equal, the system attains its maximum displacement in the shortest time. In practice it is not necessary to work exactly at the critical point, but for the purpose of mathematical investigation we shall consider this particular condition. Then

$$\mathrm{K}^2=4\mathrm{I}\mu, \tag{iv}$$

and the period of oscillation of the system, τ, is given by

$$\tau=2\pi\sqrt{(\mathrm{I}/\mu)}. \tag{v}$$

Introducing (iii), (iv), and (v) into equation (i), we get

$$\theta_{\text{max.}}=\Delta\mathrm{TB}\sqrt{(\tau^3/4\pi^3\mathrm{I}r)}.$$

This solution shows that for a given τ, $\theta_{\text{max.}}$ is independent of S, and increases as I and r decrease. These considerations lead us to conclusions very different from those indicated at first sight by equation (i). It is necessary to make the loop small so that the moment of inertia may be small and also that the wire should not be too thin so that r may be kept small.

Further, by making the radio-micrometer small, it is easier to shield it from stray external temperature effects, while the time to reach the thermal equilibrium value is small. These two considerations were of the highest importance, for in the experiments it was found that it was much more difficult to shield from the stray effects than to increase the sensitiveness to any desired amount.

Description of the Apparatus.

(i) *Suspension System* (figs. 1 and 2).—The suspension system is placed between pole pieces, N, S, of circular cross-section and separated by a distance of 3·4 mm. It is supported by a short quartz fibre, of thickness 2·0 μ to 2·5 μ. The magnetic field is produced by a double horseshoe magnet, M, M, taken from a Bosch magneto. As pointed out by Boys in his earlier papers, the greatest difficulty in the construction of the suspension system arises from the fact that, owing to the magnetism of the loop, the motion cannot be controlled by the use of thin quartz fibres. In a recent paper, Witt* has given a very elegant method for the production of non-magnetic suspension systems. This method was applied in the following manner: A copper wire, diameter 0·14 to 0·23 mm., was taken and bent into a loop, L, as shown in fig. 1. After carefully cleaning with acid and washing with distilled water, it was attached to a quartz fibre which supported a mirror. It was then placed between the sharp-pointed pole-pieces of an electromagnet, between which a magnetic field with a large gradient could be obtained. When the magnet was excited, a very large deflection of the spot of light from the mirror occurred. This deflection was due to the paramagnetism of the specimen, owing probably to the presence of small amounts of iron generally found in commercial copper. Pure copper is diamagnetic. The loop was now placed in an electrolytic bath and pure copper deposited on it. Starting with a current of 1·5 milliampères, and finishing with a current of 3 milliampères, so that the total input was from 13 to 15 milliampère-hours, specimens were obtained which gave, on test, deflections of less than 1 cm. A bath of commercial copper sulphate solution, acidulated with sulphuric acid, was used. One interesting phenomenon was observed. When the current was from 2 to 3 milliampères, the deposit was diamagnetic, but by increasing the current up to 6 to 7 milliampères, the deposit was less

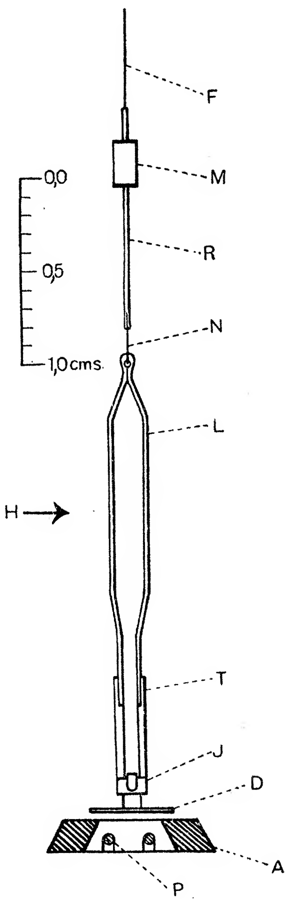

Fig. 1.

* Witt, 'Phys. Zeit.,' vol. 21, p. 374 (1920).

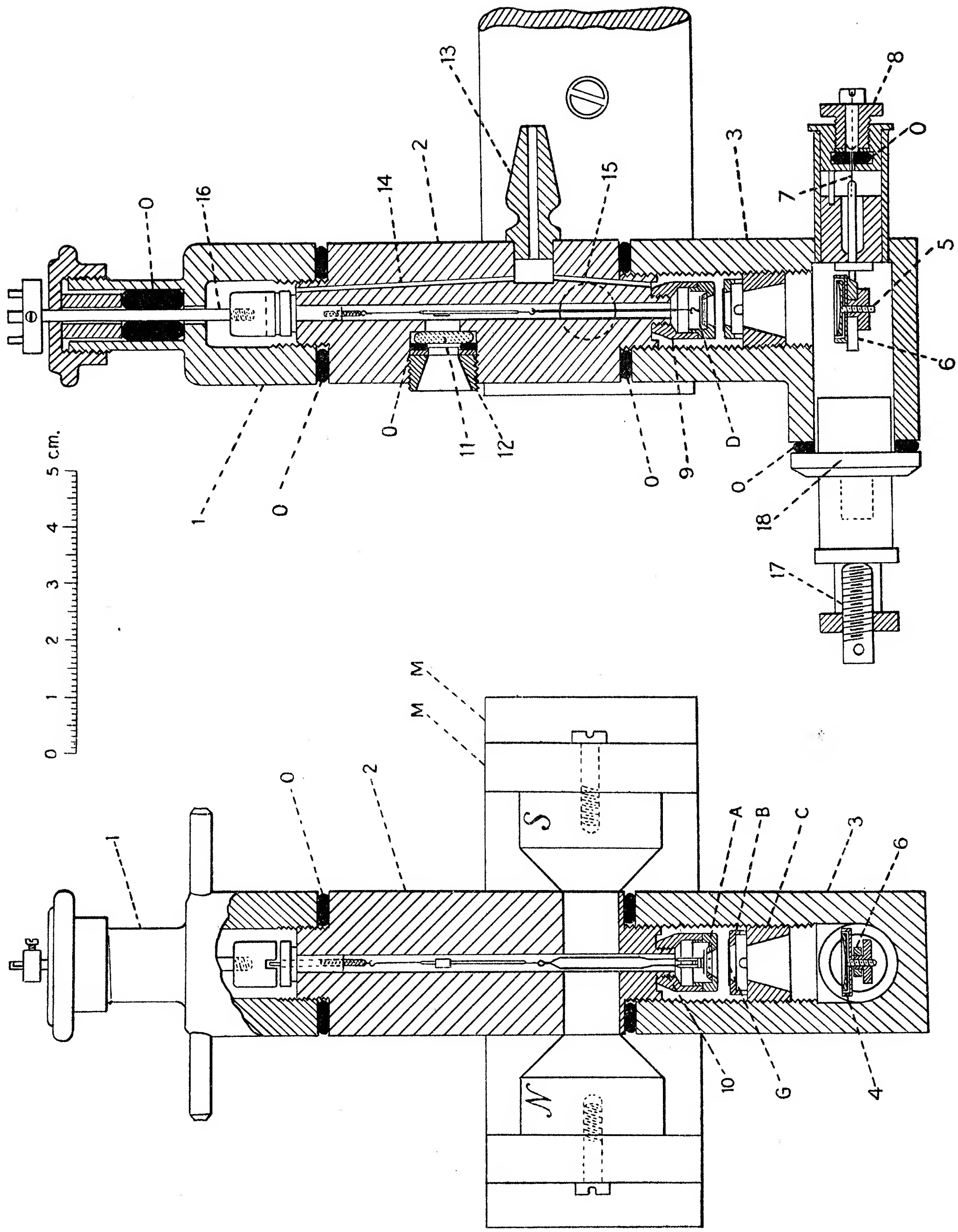

Fig. 2.

diamagnetic, and finally became paramagnetic. This is probably due to impurities in the bath, which are deposited when heavy currents are used.

To the non-magnetic loop was now soldered the thermocouple. The

alloys used in its construction were those given by Witt.* The preparation of the strips for the thermocouple was done in the following way: A small portion of the alloy was taken, placed between glass plates, fused and compressed. In such a way sheets of thickness as small as 0·01 mm. could be obtained. In practice, strips of width 0·3 to 0·4 mm. and length 3 to 5 mm. were cut from sheets of thickness 0·03 to 0·05 mm. These were soldered, by means of a soft solder, at one end to the loop at T and at the other end to a small thin silver plate, J. It is necessary to mount the thermocouple to the loop soon after its preparation, because otherwise, if left in the air, after about 3 or 4 hours the loop becomes appreciably paramagnetic, due to the deposit of dust on it. All the work on the loop must be done on a clean glass plate using brass tweezers. The thermocouple cannot be made non-magnetic, and it is essential that it should be placed as far as possible from the magnetic field, as shown in fig. 2.

To the thermocouple, T, is attached, by means of a hook, a silver disc, D, 4·5 mm. diameter, made of a silver sheet 30 mgrm. per cm.^{2} weight, so chosen to absorb the α-particles and to let the β- and γ-radiation through. The disc was attached to the system after the latter was placed in the apparatus. The loop was supported by a silver hook, N, which was sealed into a glass tube, R (diameter 0·2 mm.), to which was attached a mirror, M, dimensions 2 by 1·5 mm., made of a microscope cover-slip. The glass tube was employed by Boys, and serves a double purpose. First, it puts the mirror at a considerable distance from the thermocouple, and thus, owing to the bad conductivity of the glass, shields the couple from any heating effect of the beam of light; and, second, it keeps the mirror well out of the magnetic field.

(ii) *The Source* (fig. 2).—Beneath the plate of the thermo-junction, D, at a distance of 2·5 cm., was placed the source of RaC. This was a brass disc, 5, of diameter 1·2 cm., sometimes plane and sometimes concave, with a radius of curvature 3·5 cm. This was put in a circular receptacle, 4, the edge of which projected slightly above the source, the whole being placed on a fork, 6, which was capable of rotation about a horizontal axis. When the source was rotated 180° from the position shown in fig. 2, no α-particles could strike the plate D beneath the thermo-junction. This method of cutting off the α-rays by rotating through 180° was necessary, because using any other method, for example, a shutter, would disturb the temperature equilibrium, whereas this is not the case on rotation, since the front and back of the source are at the same temperature. A shutter was actually tried, and found to produce an extra deflection of 1 to 2 mm., but

* Witt, *loc. cit.*

rotating the source produced no deflection whatever. The rotation was produced by a device, not shown on the figure, placed outside the apparatus, operated by means of two Bowden cables,* arranged in such a way that the source could be rotated rapidly and without any appreciable vibration of the apparatus.

Three diaphragms, A, B, C, were placed in the path of the rays. The first, A (see figs. 1 and 2), was made of silver, and was placed at a distance 0·4 mm. from the plate D. The aperture of this diaphragm was 3·5 mm. diameter, whereas that of the plate D was 4·5 mm., so that all the α-particles passing through the diaphragm reached the plate. In this arrangement it is seen that only 1/800 of the α-particles emitted from the source reach the plate. The middle of the diaphragm was crossed by two thin silver wires, P, the purpose of which will be considered later.

The diaphragm, B, was of copper, and was covered by a very thin aluminium foil, G, of stopping-power equal to 1 mm. of air. This foil shielded the thermocouple from the heat radiation from the source, and owing to its small thickness, did not seriously affect the α-particle. The foil G thus separates the lower part of the apparatus from the upper, and so prevents the circulation of any convection currents.

(iii) *The Body of the Apparatus.*—In order to vary the amount of energy lost by the α-particle between the limits required, the pressure of the gas contained within the apparatus had to be varied from 1 cm. of mercury to 3·8 atmospheres. The apparatus has thus to be air-tight, and this was accomplished by means of the rubber rings shown at O.

Since changes in the pressure of the gas are accompanied by changes in temperature, it is necessary to wait some time for the system to reach thermal equilibrium. In order to shorten this time the volume of the gas space must be as small as possible consistent with the fact that the α-particle has to pass through a certain amount of gas, and with the fact that the suspension system occupies a certain volume. As is seen from fig. 2 these ideas were embodied in the construction of the apparatus, the gas space within which was about 5 c.c. The body of the apparatus was made of solid brass so as to have a thermal capacity large compared with that of the enclosed gas.

Another idea embodied in the construction of the apparatus was to shield the thermocouple from the possible variations in temperature occurring within the room. For this purpose we have to avoid any difference in the temperatures of the ends of the thermocouple, JT. *A priori*, it is clear that to keep two points at the same temperatures they must be surrounded by layers

* These cables consist of a spiral steel tube inside of which a steel wire can move, chiefly used on motor cycles.

of material possessing alternately good and bad thermal conductivity. This was accomplished in the following manner, as shown in fig. 2. The thermo-junction was contained within a cylindrical chamber, 9, made of copper or silver. This chamber is surrounded by air except at the junction, 10, with the body of the apparatus. The second good conductivity layer is the body of the apparatus itself made of brass. The whole of the apparatus including the magnets and the device for rotating the source was contained within a copper box with double walls with water between. Under these conditions the equilibrium of the system was so good that the zero remained constant for periods of several hours.

The body of the apparatus was made of three parts, 1, 2, 3. The lower part, 3, was provided with an opening through which the source was inserted, and which could be rapidly closed by means of the brass stopper, 18, and tightened by means of the single screw, 17. The axle of the source terminated in a pin, 7, passing through a piece of rubber which could be compressed by means of the nut, 8, thus keeping the apparatus tight, and the whole could be rotated from the outside by means of the device already mentioned.

The central portion, 2, was supported by means of the circular pole pieces, N, S, which were screwed to the fixed magnets, M, M. Opposite the mirror of the suspension system an opening was made, which was covered by a plane glass plate, 11, waxed in and kept tight by means of the nut, 12. To the lower central part, 10, different heating chambers, 9, could be attached.

By means of the nozzle, 13, the pressure of the gas within the apparatus could be varied. The gas entering the apparatus had first to pass through the channels, 14 and 15, which were made long and narrow in order that the gas could readily attain the temperature of the apparatus.

The upper portion, 1, consisted of a cap, which was screwed on to the portion, 2, after the suspension system was set up. It contains a device, 16, for adjusting the zero of the suspension system from the outside.

(iv) *The External Apparatus.*—The nozzle, 13, was connected, by means of a rubber tube, in series with a glass reservoir of 300 c.c. capacity, which kept the pressure of the gas within the apparatus fairly constant. The reservoir was wrapped in cotton-wool, this being done because, without it, the temperature variations occurring in the room were transmitted to the reservoir, thus causing changes of pressure of the gas within. This change of pressure is transmitted to the inside of the apparatus which in turn causes changes in temperature therein. By placing one's finger on the reservoir this phenomenon could be easily observed, for a deflection of 1 to 2 cm. was at once produced. On wrapping up the apparatus it was possible completely to get rid of the small movements, of the order of 0·4 to 0·5 mm., of the spot of

light on the scale. The apparatus is, in fact, extremely sensitive to changes of pressure, and merely squeezing the rubber tube, which corresponds to a change of pressure of the order of 1/100th of a millimetre, caused a deflection of 40 to 50 cm.

The pressure was observed by means of a simple mercury manometer which was graduated to read directly from + 2·8 to −1 atmospheres. The gas was gradually let out of the apparatus by means of a special tap.

The spot of light was focussed on to a scale, at a distance of 1·3 metres, by means of an eye-piece lens placed close to the opening, 11. The light came from a 100 c.p. pointolite lamp, and in order to absorb the heat in the beam, a glass vessel with parallel walls in which water was circulated, was placed near the lamp. Beyond the glass vessel a short focus lens was placed in order to get a parallel beam of light. This beam now passed through a slit of 1 cm. long and 0·2 mm. wide, a good image of which was observed on the scale. With this arrangement no heating of the apparatus by the light was observed.

Method of Observation.

The source of α-rays was Ra (B+C) obtained by exposing the brass disc, 5, to radium emanation. Its activity, measured by γ-rays, was usually equivalent to from 25 to 45 mgrm. Ra. I am greatly indebted to Mr. G. A. R. Crowe for the preparation of these sources. The source on removal from the emanation was cleaned, measured, and inserted in the apparatus. The apparatus was then adjusted to the proper pressure, or in the case of CO_2 first evacuated to a pressure of 1 mm. the gas then being admitted to the required pressure. After about 10 minutes the apparatus had reached a state of thermal equilibrium and readings were possible. The total time that elapsed between the removal of the source from the emanation and the commencement of observations was from 20 to 25 minutes. In order to save time, a photographic method of observation was arranged, so that it was not necessary to wait until complete thermal equilibrium was attained. The spot of light was projected on a narrow slit behind which a long strip of sensitive paper was moved at a rate of 1 to 1·5 cm. per minute. In attaining thermal equilibrium the spot of light was slowly moving across the slit, and exposing the system to the rays by rotation of the source, photographs as shown in fig. 3 were obtained. From these photographs it is easy to obtain the deflections produced by the α-particles alone. It is only necessary to draw an envelope to the displacement produced by the α-rays and measure the distance from the undisturbed curve.

The photographic method of observation possesses several distinct advantages. It provides an accurate way of recording the time, knowledge

of which is necessary in calculating the decay of the source. For this purpose a small electric lamp was placed in front of the slit which, by means

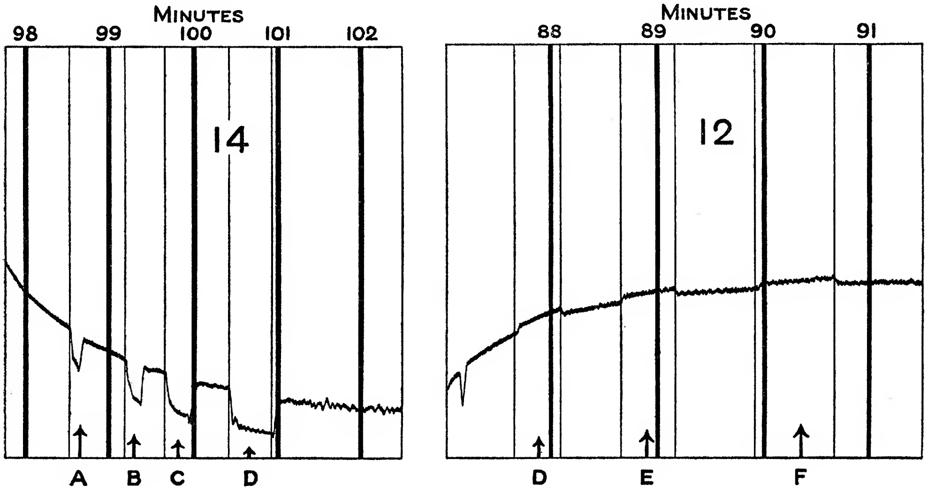

FIG. 3.

of clockwork, gave a flash every minute. These flashes produced the dark lines shown in the photographs.

The photographic method also permits of the mean value of the observations being observed in spite of the fluctuations produced by vibration of the apparatus.

After obtaining three or four readings, the pressure was reduced to a new value and the procedure repeated. After changing the pressure, the time to reach approximate equilibrium and take the next observation was from 4 to 6 minutes. Hence if the total time taken from the removal of the source from the emanation to the last observation is 100 to 110 minutes, it is possible to obtain from fifteen to nineteen points on the curve, for each of which some two to four observations could be made.

In all the experiments the pressure was reduced to obtain successive readings. The lowest pressure was not less than 1 to 2 cm., for with lower pressures the charge acquired by the suspension system cannot be readily lost by ionisation in the surrounding space, and the electrostatic couple thus produced causes inaccuracies in the readings. The gases used were air and carbon dioxide taken from a cylinder. The accuracy with which the photographs obtained could be measured up, using a magnifying glass, was 1/10 mm. The observed deflections were then corrected for the decay of the source. The distance between the plate D and the source was measured by means of a cathetometer.

Knowing the temperature and the pressure within the apparatus, the amount of gas traversed by the α-particle before it reaches the plate D can be readily calculated. These distances were then expressed in terms of pressure 760 mm. and temperature 15° C., and were plotted as abscissæ against the observed deflections as ordinates. The relations obtained are shown in Diagrams I, II, III. If the deflection is proportional to the kinetic energy

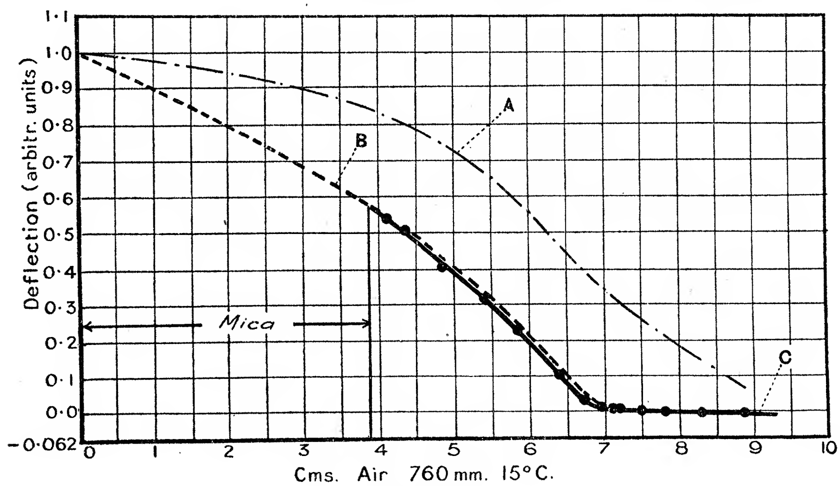

DIAGRAM I.

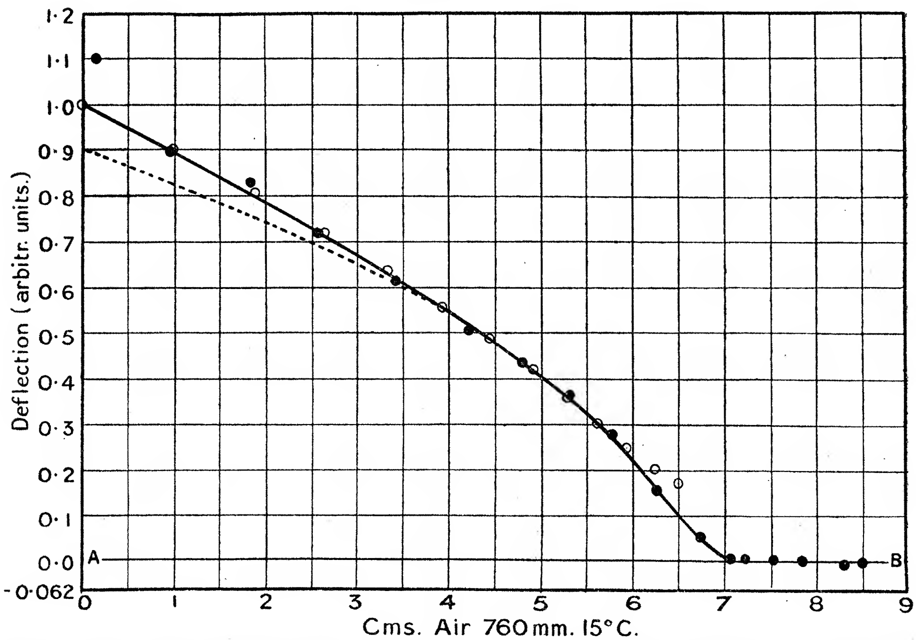

DIAGRAM II.—Energy distribution curve in air. ○ ... Marsden and Taylor ; • ... Kapitza ; – – – – – ... Henderson.

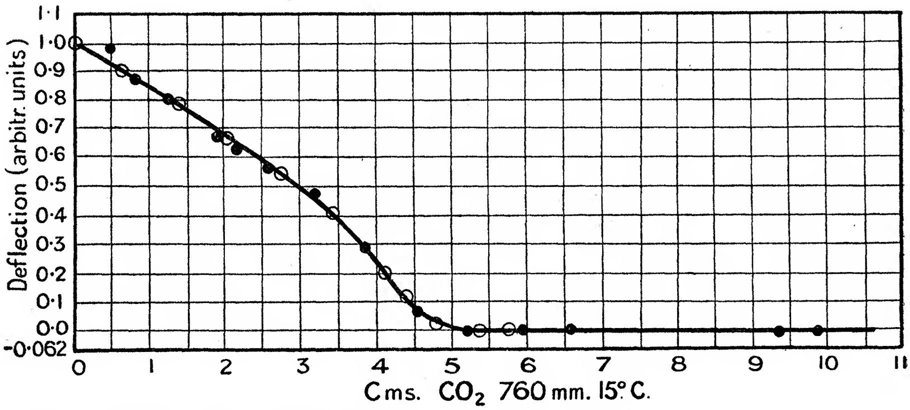

Diagram III.—Energy distribution curves in CO_2 and air. • ... CO_2 ; ○ ... Air.

of the particle, then the curves will represent the distribution of energy of the α-particle at different parts of its range.

Stray Effects.

Before attempting an interpretation of the curves obtained it is necessary to examine the stray effects produced in such a sensitive apparatus. We will first consider any occasional effects and finally the systematic stray effects.

We have considered the occasional stray effects produced by variations in temperature in the room, and the heating effect of the beam of light; but, due to the precautions previously mentioned, these effects caused no appreciable error, and never interfered with the observations. Some inconvenience was caused by variation of the pressure within the apparatus, due to small leaks of the order of 1 mm. in 3 or 4 hours. According as the pressure within the apparatus was greater or less than atmospheric the zero of the suspension system had a new value, but remained quite steady. It was feared that this variation in the zero might produce a variation in the sensitiveness of the apparatus. On the other hand, because the suspension system was not entirely non-magnetic, it was feared that the deflections produced might not be proportional to the heating produced in the plate D by the absorption of the α-particles. To examine these points the following experiment was performed. Beneath the thermocouple a very thin platinum wire was placed through which different currents were sent. The results obtained showed that the deflection was quite proportional to the square of the current passing, and that the sensitiveness of the apparatus was quite independent of the pressure of the gas. It is thus seen that these effects produce no error in the readings obtained.

On account of the small size of the suspension system, and the consequent

unsteadiness produced in it by vibrations of the building, it was always necessary, in order to obtain good results, to work during the evening.

The first systematic stray effect is due to the fact that only a small fraction (about 1/800) of the total number of α-rays emitted by the source reached the plate D. The rest of the rays lose their energy in heating the body of the apparatus. Since this amount of energy is considerable, if no special precautions were taken the stray effect would be large. The diaphragms, B, C, were entirely for the purpose of protecting the heating chamber, 9, from this effect. To obtain some idea of the order of magnitude of the effect, the following experiment was made. The diaphragms B and C were removed and a loop of thin wire placed some distance below the heating chamber, through which a current was passed of such a magnitude as to produce approximately the same heating as that produced by the α-rays. It appears that the effect does exist, but it does not, on account of the large thermal capacity of the apparatus, reach its maximum value until after 5 minutes. The time taken for the suspension system to reach its maximum deflection, when the α-rays are absorbed in the plate D, is, however, from 5 to 10 seconds. On account of this difference in time we can appreciate the magnitude of the stray effect. In fig. 3, photograph 14, four observations are noted, A, B, C, D, which correspond to exposures of 5, 10, 20, 30 seconds. No appreciable differences in the deflections are observed. The final small kicks in the deflections are due to the fact that in the act of rotation one edge of the source comes closer to the plate.

A further systematic stray effect is due to the fact that the α-particles, before striking the plate D, heat the surrounding air. This effect may change entirely the nature of the phenomenon, unless proper precautions are taken. The broken curve, A, Diagram I, represents the results obtained in a previous experiment without the use of diaphragms. This curve shows that the deflections towards the end of the range of the α-particles are greater than one would expect, and this is due to the fact that the α-particles heat the air in the neighbourhood of the edges of the plate. In addition, the curve extends beyond the end of the range of the α-particles, and this is due to the heating of the air immediately beneath the plate. The diaphragm A was inserted in order to avoid these two stray effects. As already noted, the diameter of the aperture in A was less than that of the plate D, and the relative positions of A and D prevented any α-particles from getting near the edges of the plate. To avoid the heating of the air beneath the plate, two fine silver wires, P, crossed the diaphragm at a distance 0·7 mm. from the plate. On account of the high thermal conductivity of these wires, the heat produced in the air was prevented from reaching the plate, and, instead, was

conducted to the body of the heating chamber. With these precautions the magnitude of these stray effects was reduced below the experimental error, as can be seen from the results of the following experiment:—

The source was covered by a mica sheet of stopping-power equal to 3·75 cm. of air, and the curve C obtained. The broken curve B was obtained without the use of the mica sheet. In the former case the whole range of the α-particle was obtained with a pressure just one-half that in the second case. Consequently, the heat produced in layers of air of equal thickness below the plate should be twice as great in the second case as in the first, and so the magnitude of these stray effects ought to have the same variation. The good agreement of the curves B and C shows that the effects could not be detected.

The final systematic stray effect is due to the absorption of the β-rays, and will be considered later in a special section.

Sensitiveness and Accuracy of the Method.

The sensitiveness of the apparatus was considerably reduced by the use of the diaphragm, A, and the silver wires, P. This is easy to understand. From equation (i) it is seen that the deflection, θ, is proportional to the increase in temperature, ΔT, of the thermo-junction. This increase in temperature is given by

$$\Delta T = \frac{Q}{K_a + K_j},$$

where Q is the amount of heat given to the plate per second, K_a, K_j are respectively the whole thermal conductivities of the air between the plate, D, and the heating chamber, 9, and the strips forming the thermo-junction. In practice K_j is small compared with K_a. Putting the diaphragm, A, nearer the plate, K_a is considerably increased, causing a consequent reduction in the sensitiveness of the apparatus. The sensitiveness of the apparatus was found to be about four times greater when the diaphragm, A, was omitted. It was possible to overcome this loss of sensitiveness in the following manner:— From equation (i) it is seen that the deflection produced is almost inversely proportional to the resistance of the thermocouple (the resistance of the loop is small), and making the strips of the thermocouple short and thick, r, is diminished. However, this increases K_j, since $K_j \propto 1/r$. Diminishing r increases the sensitiveness of the apparatus, but increasing K_j does not appreciably affect ΔT, since K_j is always small compared with K_a. We thus see that the thermo-junction should not be made of thin strips. However, this method of overcoming the difficulty has two disadvantages which, in practice, limit the sensitiveness of the apparatus.

First, we see from equation (i) that the deflection, produced by the stray effects within the apparatus, is proportional to the term

$$B \frac{S \dot{H}}{r \mu}$$

and is independent of K_j and K_a. Decreasing r simply increases the above term, and we obtain finally a system which is very sensitive to stray effects, and which takes a long time to attain thermal equilibrium.

Second, making the thermo-junction of thick strips, it was difficult to produce a non-magnetic suspension system.

The sensitiveness of the apparatus in the experiments was as follows:— The maximum deflection produced per milligram of RaC on the source was 1·4 mm. in CO_2 and 0·95 mm. in air. The deflection in air is less on account of the higher thermal conductivity. Using 40 mgrm. of RaC as the source, the maximum deflections produced were 5·6 cm. in CO_2 and 4 cm. in air. On the photographs a deflection of 1/10th of a millimetre could be measured. Taking into account the decay of the source, after removal from the emanation, this shows that it is possible to measure about 1/300th of the initial energy of the α-particle. As the readings were obtained working back from the end of the range the deflections observed were generally between 5 and 10 mm. Thus the accuracy of measurement of a single observation was about 2 per cent. As each point was the mean of several observations it is probable that the actual accuracy is better than this. The error due to the fact that some of the α-particles had to travel longer distances to the plate, was reduced to about 1 per cent. by using a concave source.

Discussion of Results.

The full curve, Diagram II, represents one of the characteristic curves obtained for air. The ordinates of the curve decrease continuously until a range of about 6·95 cm. is reached, afterwards remaining constant. This final constant deflection, which is about 5·8 per cent. of the total initial deflection, is due to the β-rays as discussed in the next section. To separate the effects of the β-rays from those of the α-rays, it is only necessary to draw the horizontal line, AB, which is the prolongation of the observed β-ray effect. This is probably quite legitimate, since the β-rays are only slightly absorbed in the air-space traversed by the α-rays. Thus the curve referred to AB as axis will represent the true energy distribution of the α-particles. From these considerations it is seen that the α-particle has no energy beyond the end of its range as determined by ionisation methods. A similar curve was obtained for CO_2, as shown in Diagram III. Allowing for the β-ray effect the

range for the α-particles is found to be 4·75 cm., which is in good agreement with previous determinations. Changing the scale of the abscissæ for the curve obtained with air in the ratio 4·75 to 6·95, the curves for air and CO_2 (see Diagram III) were found to coincide very nearly. This result shows that the loss of energy of the α-ray in CO_2 is governed by the same laws as in air.

An attempt was now made to compare the curves obtained with those obtained by the ionisation method. If the α-particle produces N-ions per centimetre path, then in a distance dx it will produce N dx-ions, and if the energy to create a single ion is E, the energy required in this production will be

$$\mathrm{EN}\, dx.$$

If W is the total energy of the α-particle, W_x its energy after travelling a distance x, then if all the energy lost is due to ionisation,

$$W_x = W - \int_0^x \mathrm{E\,N}\, dx.$$

If we assume that the same amount of energy is required to produce an ion at all points of the range, then we obtain

$$W_x = W - E\int_0^x N\, dx.$$

The dependence of N on x is given by the ordinary ionisation curves, the best being those obtained by Henderson* which were used in the evaluation of the integral. The curve calculated in this way is shown by the broken line on Diagram II. It is seen that after 4 cm. of the range, the curves are in very good agreement. This shows that towards the end of the range the average energy required for the production of each ion is constant, and we can assume that the loss of energy is proportional to the ionisation produced. Near the beginning of the range, the Henderson curve shows a marked departure from the observed curve, indicating that the energy required to produce an ion is greater for the swifter rays. We can thus say that the energy required for the production of an ion by an α-ray of range 7 cm. is, on the average, about 10 per cent. greater than that required by an α-ray of range 3·5 cm. This leads to the conclusion that the α-rays with high velocities are better able to eject electrons from inner orbits of the atom, which process would require more energy than the ejection of electrons from the outer orbits. This confirms the theory advanced by Bohr† of the passage of α-rays through matter.

* G. H. Henderson, 'Phil. Mag.,' vol. 42, p. 538 (1921).

† N. Bohr, *loc. cit.*

A further comparison can be drawn between the present results and those obtained by Marsden and Taylor.* These latter are shown by open circles on Diagram II. These points are obtained from Table III, column 5, p. 448, of Marsden and Taylor's paper, which they state are probably the most exact values, and it is seen that, up to a range of 6 cm., the agreement between their curve and mine in Diagram II is very good. Beyond 6 cm. they no longer agree, the present experiments giving lower values for the energy. In the following Table are compared the numerical values obtained by Marsden and Taylor and in the present work.

	Range in air......	5·78 cm.	6·26 cm.	6·50 cm.	6·72 cm.	7·07 cm.
Kapitza	V	0·522	0·400	0·316	0·244	Less than 0·084
	V^2	0·273	0·160	0·100	0·059	Less than 0·007
Marsden and Taylor	V	0·527	0·450	0·415		
	V^2	0·278	0·202	0·172		

where V, V^2 are expressed in terms of initial values. The disagreement between the values of V^2 when the range is 6·50 cm. is 72 per cent., and this cannot be explained by experimental errors. A complete explanation of this disagreement is not easy, but the following considerations may help to throw further light on the problem.

First, in the present experiments, the average energy of the α-rays in a beam was measured, and towards the end of the range it is possible that the increased scattering may affect the result. On account of this scattering some α-particles may be deflected away from the plate, causing a diminution in the total number which should fall on the plate. This diminution should depend on the distance from the plate at which scattering becomes appreciable, and should thus be quite different in the case when the rays pass direct through air to the case already mentioned, when they first pass through a mica sheet of stopping-power equal to 3·75 cm. of air. The good agreement between the curves B, C, Diagram I, shows, however, that any difference produced is too small to measure, so that scattering considerations will not explain the discrepancy.

Second, we have to consider the lack of homogeneity in the beam. On theoretical grounds, the loss of energy of an α-particle is due to interaction with a very large number of atoms, and any deviation from the statistical mean should thus be very small. We are thus led to anticipate that the

* E. Marsden and T. S. Taylor, *loc. cit.*

beam should be fairly homogeneous. Practically, however, it is a difficult matter to obtain a homogeneous beam of α-rays, owing to the lack of uniformity in the thickness of the material used to absorb them. From the energy curve, shown in Diagram II, it is seen that, towards the end of the range, from 6 to 6·5 cm., an error of 4 per cent. in the range causes an error of 100 per cent. in the energy. In the experiments of Marsden and Taylor, as pointed out by the authors, the scintillations towards the end of the range became fainter and fainter, so that it was impossible to detect α-particles with energies less than 0·172 of the initial energy. Thus it seems probable that, in the α-ray beam used by Marsden and Taylor, there were always some rays with velocities greater than the mean, due to the lack of uniformity in the thickness of the absorbing material, and on account of the loss of sensitiveness of the apparatus, only these swift particles, which constitute a small fraction of the total number, could be observed. The large variations in the measurements of the speeds of the α-rays towards the end of the range, using as stopping materials mica, aluminium and gold, support this view.

Further, Marsden and Taylor have pointed out that the inaccuracies in their work may be due to the fact that some of the α-particles are singly charged owing to recombination. There is some reason to suppose that this does happen, and perhaps the α-particle gains and loses electrons several times during its passage through matter, and towards the end of the range the number of recombined particles is increased. If we suppose that the majority of α-particles, whose energy is less than 0·172 of the initial energy, are singly charged, this will account for the abrupt limit of the observations of Marsden and Taylor.

In the present experiment the α-ray beam should be fairly homogeneous, on account of the fact that the stopping material was a gas. Any lack of homogeneity in the α-ray beam arising from variations in velocity or from differences in the charge carried will, however, produce no effect, since a mean value was measured, and so the velocities observed should agree most closely with those of an "ideal" α-ray beam.

Finally, it is interesting to compare Marsden and Taylor's curve with that obtained from the ionisation curve in the manner already described. We find that the curves fail to agree beyond a range of 6 cm. in such a way that, at 6·5 cm., the energy required for the production of an ion is twice as great as that required at 6 cm. It is difficult to account for this variation on theoretical grounds.

The Heating Effect of the β-Rays.

In the previous section, we have assumed that the deflection obtained after the end of the range of the α-rays was due to the heating effect of the β-rays, and the line AB was drawn in order to separate the two effects. These considerations are so important to the correct interpretations of the results, that special experiments were carried out to justify the assumption. It is certain that this deflection after the end of the range cannot be due to the α-rays. On Diagram III, which represents the curve for CO_2, two points are obtained at distances 9·6 and 10 cm., to produce which the α-particle would, after the end of its range, have to pass through a layer of CO_2 of stopping power greater than that of the plate D of the thermo-junction. But the deflections corresponding to these two points are only about 20 per cent. less than those immediately after the end of the range. This shows that the effect produced after the end of the range is due to a radiation of greater penetrating power than the α-radiation. For a more detailed examination of the effect the following arrangement was set up.

A small thin-walled glass bulb, diameter 3 mm., shown at 2 in fig. 4, was filled with 46 mgrm. of emanation, the thickness of the walls being just sufficient to absorb the α-rays. The bulb was fixed by means of a little wax, 3, into a brass receptacle, 1. The opening at the top of the receptacle could be covered by successive layers of aluminium foil, which could be fastened down by means of the cover, 5. This arrangement now replaced the source on the fork, 6, fig. 2. Rotating this arrangement, the β-rays could be allowed to fall on the plate at will. In this way deflections were obtained of the same order of magnitude as those found in the previous experiments after the end of the range of the α-particles. The apparatus was now divided into two parts by means of a thin aluminium sheet of thickness 0·045 mm., placed beneath the diaphragm, C, fig. 2. The deflection was reduced but did not disappear, which shows that the effect could not be due to any heat radiated from the source, or to any convection currents in the gas.

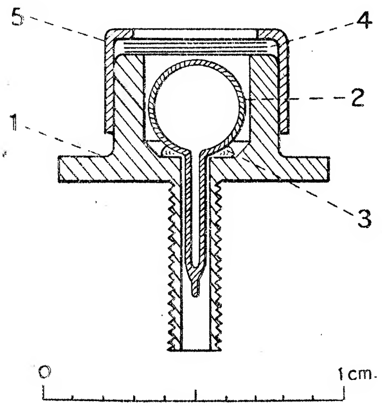

Fig. 4.

Afterwards a disc of lead, thickness 0·11 mm., was attached to the plate, D. The deflection now produced was about 1·35 times greater, apparently due to the greater absorption of the β-rays. Removing the diaphragm, A, the

deflection was considerably increased and it was possible to obtain a curve for the absorption of β-rays in aluminium. By altering the number of foils, 4 (fig. 4), each of thickness 0·045 mm., Diagram IV was obtained. From this curve it is

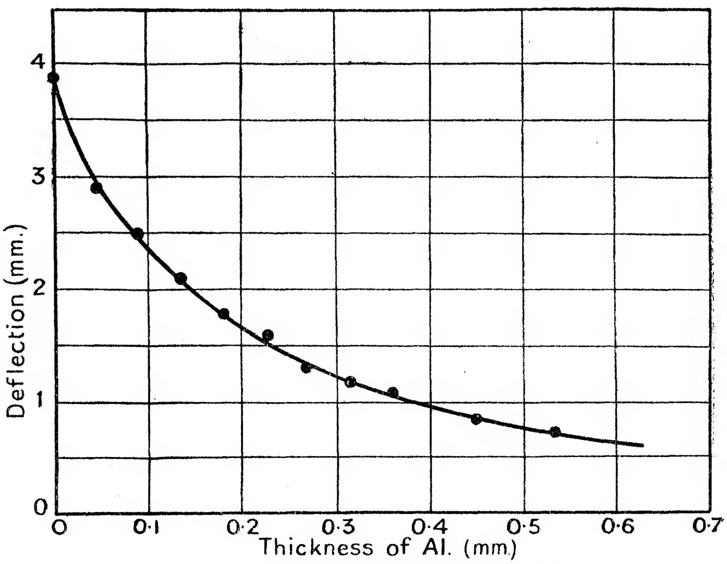

DIAGRAM IV.—Absorption of β-Rays in Aluminium.

possible to calculate the coefficient of absorption, μ, for β-rays in aluminium. We find, at the beginning of the curve, $\mu = 56$, and at the end $\mu = 26$, which is in good agreement with the limits, $\mu = 65$ to $\mu = 13$, determined by ionisation methods.

All these experiments confirm the original assumption. From Diagram I and the previous experiment a very rough estimate can be formed of the energy carried by the β-rays compared with that carried by the α-rays. Curve C, Diagram I, shows that the β-ray effect is about 6·2 per cent. of the α-ray effect. Taking into account the increased absorption in the lead plate this value becomes 8·4 per cent. The value obtained by Rutherford and Robinson* is 10·9 per cent. The difference of 25 per cent. between these values cannot be regarded as established, because the present method is open to two objections. First, it is quite probable that the lead plate does not absorb all the β-rays, but this is not sufficient to account for such a large difference. Second, on account of the scattering of the β-rays by the plate D a portion only of the energy in the β-ray beam is converted into heat. On the other hand, β-rays scattered from the walls of the apparatus and falling on the plate will compensate for this to some extent. The complicated shape

* E. Rutherford and H. Robinson, *loc. cit.*

of the interior of the apparatus renders it difficult to make an exact estimate of the magnitude of these scattering effects. Further experiments, using an apparatus of more suitable shape, are needed to settle the point.

Analogy to the Ionisation Curves.

The magnitude of the stray effect due to the heating of the air in the neighbourhood of the thermocouple led to the idea of measuring the heating effect at different parts of the range, thus providing an analogy with the ordinary ionisation curve. For this purpose the heating chamber 9, fig. 2, was replaced by a special type shown in fig. 5. The actual chamber, 2, was only 3 mm. deep, containing an opening 4·5 mm. diameter crossed by two silver wires, 4. The thermocouple, 1, projected into the chamber through an opening, 2 mm. diameter, in the cover, 3. In this way it was possible to isolate a small quantity of gas and to measure the heating therein produced. Altering the pressure in the apparatus changes both the mass of gas contained in the heating chamber and the amount of gas through which the α-particle has first to pass. Working in the same way as before, curve 1 shown in Diagram V was obtained. To obtain from this the analogy to the ionisation curve it is necessary to apply some corrections. First, some α-particles struck the thermocouple directly, thus producing extra heating. It is possible to separate this stray effect from the real effect in the following manner. The point A on the curve corresponds to the full exhaustion of the apparatus and the whole deflection is due to the α-rays which strike the thermocouple. If we now draw from A the energy curve, 3, similar to that previously obtained, the difference between the ordinates will represent the energy due to the heating of the air in the heating chamber. The correctness of this interpretation was tested experimentally in the following way:—

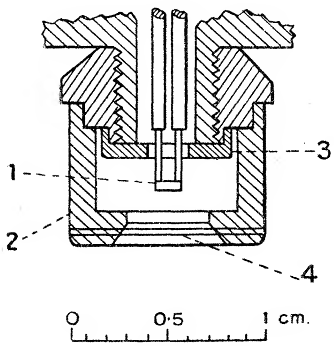

FIG. 5.

A small silver plate, of dimensions 2 mm. by 1 mm., was supported on the silver wires, 4, thus partly shielding the thermocouple from the direct α-ray beam. In this way the curve 4 was obtained, and it is seen that the initial deflection is considerably reduced. These results cannot be used in further calculation, due to the fact that the sensitiveness of the apparatus was reduced by one-half, because the plate stopped some α-particles which would have heated the gas surrounding the thermocouple. Correcting

curve 1 by means of curve 3, we can thence obtain the deflection per unit mass of heated gas by dividing the ordinate by the density. In this way the continuous curve in Diagram VI was obtained.

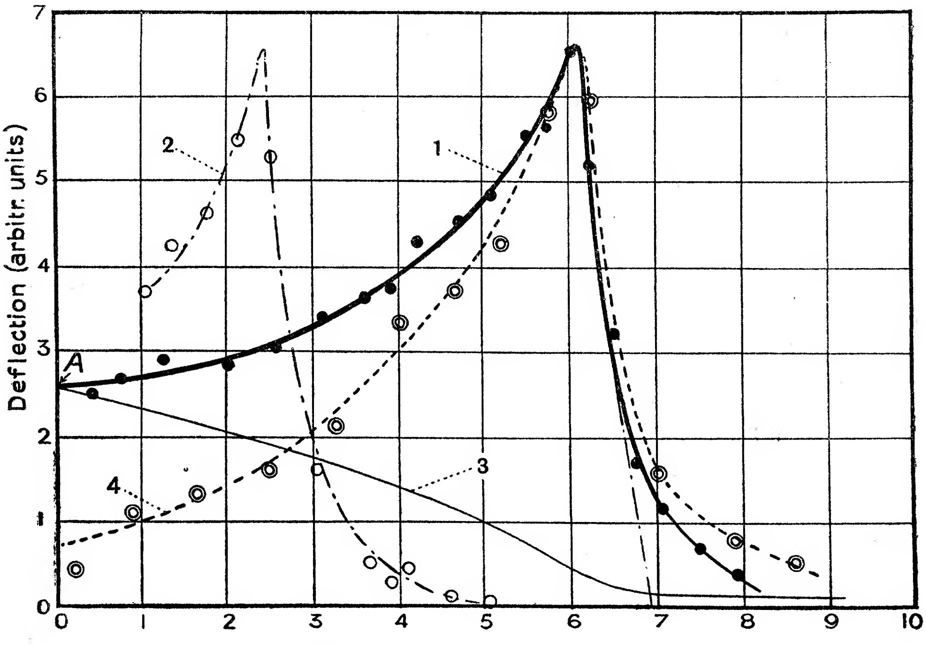

DIAGRAM V.

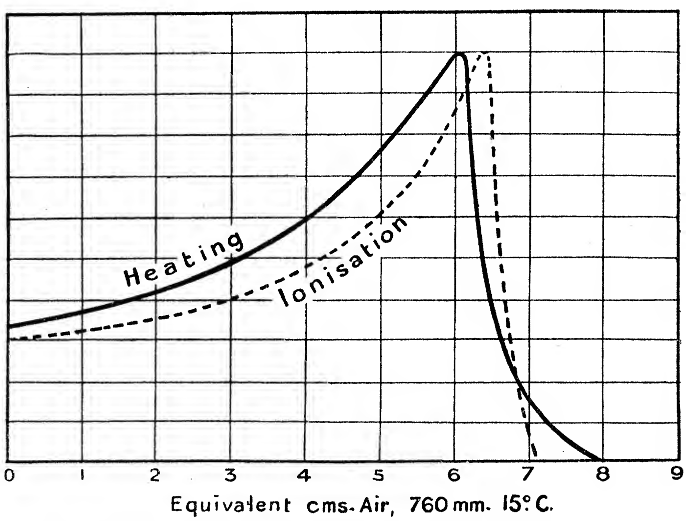

DIAGRAM VI.—Analogy to ionisation curve. ——— ... heating curve ; – – – – ... ionisation curve.

Before this curve can be compared with the ionisation curve, it is necessary to establish the end of the range. This was done in the following way: A mica sheet of stopping-power equal to 3·75 cm. of air was placed over the source and the curve 2 obtained. The slope of this curve beyond the maximum is very similar to that of curve 1. The distance between these two portions of the curves is equivalent to 3·75 cm. stopping-power of air, and thus we can deduce the scale of abscissæ, fixing the range at 6·95 cm. In this way, taking into account the pressure, it is found that the end of the range of the α-particles is at a distance 0·8 mm. below the thermo-junction. This result is to be expected, because of the high thermal conductivity of the thermocouple and the opening, 4, in the chamber. Having fixed the end of the range, we can now compare the curve with that obtained by Henderson.* This is represented by the broken curve in Diagram VI.

The curves appear to possess the same general characteristics but do not fully agree. This is due to the fact that, in the present experiments, observations were not made on a single point, but a mean taken over a definite region, a, about 0·12 of the total distance between the source and the thermocouple. When an allowance is made for this distribution, the shapes of the calculated and observed curves are very similar.

Further speculation in regard to the curve obtained is of little purpose owing to the inaccuracies in the experiment. These inaccuracies are due (i) to the fact that the chamber measured the heating over a considerable portion of the range; (ii) to the fact that the deflections obtained, using CO_2, were always small, of the order 4 to 5 mm., giving an accuracy of 2 to 3 per cent.; (iii) to the fact that, in order to obtain the curve, several operations have to be performed which probably considerably increase the error.

It is interesting to note the sensitiveness of the apparatus as used in obtaining the above curve. Fig. 3, curve 12, represents one of the initial points obtained on curve 1, Diagram V. The deflections are due mainly to the α-particles which strike the thermocouple directly. The number of α-particles producing this deflection of 1 mm. was approximately calculated to be 2000 to 3000 per second. This corresponds to a rate of heating of the order of 10^{-9} calories per second.

Summary.

(1) The construction of a sensitive radiomicrometer, and its application to the measurement of the distribution of energy in an α-ray beam is described.

(2) With the apparatus, the energy distribution in an α-ray beam in its

* G. H. Henderson, *loc. cit.*

passage through air and CO_2 has been determined, and it has been shown that, within the limits of the experimental error (1 to 2 per cent.), the same law governs the distribution in the two gases.

(3) Immediately beyond the end of the range, the α-particles have an energy not greater than 0·7 per cent. of the initial energy.

(4) A comparison of the energy distribution curve with that obtained from the ordinary ionisation curve, shows that α-particles with high velocities on an average expend more energy in the production of an ion than those moving with low velocities.

(5) A comparison of the energy distribution curve with that obtained by the measurement of the velocities of the α-particles by deflection in a magnetic field, shows that, up to a range of 6 cm., the curves are in good agreement, but that beyond this point the energy curve gives distinctly smaller values. An attempt to explain this discrepancy has been made.

(6) The heating effect of the β-rays was detected, and by means of a modified apparatus the energy absorption curve in aluminium was determined.

(7) The heating produced in CO_2 over different portions of the range was measured, and in this way curves very similar to the ordinary ionisation curves were obtained.

The passage of α-particles through solid bodies will be described in another paper.

It is a great pleasure to thank Sir Ernest Rutherford for permitting the work to be carried out in the Cavendish Laboratory, and for his active interest and kind advice during its progress. I am also deeply indebted to my teacher, Prof. A. F. Ioffé, for providing the opportunity to work in Cambridge. My best thanks are due to Mr. M. H. Belz for help in the composition of the paper.